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Assessment of Very High Cycle Fatigue (VHCF) Effects in Practical Applications

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Abstract

Fatigue designing of high-stressed engine components is a key factor for reliable power train systems in automotive industry. In this context load assumptions are very important since this is attended with a pre-designing of important machine elements. Load analyses are done usually by experimental methods since the accuracy of load simulations are often not precise enough. For example concerning VHCF problems, modern high pressure pumps for gasoline direct injection systems have load spectra with a large amount of cycles up to 10^9 including a very powerful shape of the load spectra.

At the same time it is necessary to consider the properties of fuels in service since they might affect the fatigue strength significantly. For example ethanol-based gasoline fuels are used in a lot of countries worldwide and may lead to significant corrosion fatigue effects. In addition it is well known that material inclusions play an important role for the VHCF behaviour especially for high-strength steels. Both effects are superimposing at the surface of high loaded components.

This paper deals with possibilities to avoid VHCF problems of components in service to maintain reliable systems.

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Keywords: Very High Cycle Fatigue (VHCF), automotive components, fuel injection, bio-fuels, corrosion fatigue, testing concepts, fatigue design concepts

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1. **Introduction**

Very High Cycle Fatigue (VHCF) is a topic of material research effort since more than two decades. The focus is on studying material damage processes and the understanding of relations between loading and material state, especially concerning the role of inclusions and the material microstructure. The main motivation for these efforts was the exposition of components – one of the first have been helical springs - with very high cycles in practical use, and the unexpected fatigue failures of these components at very high cycles.

From the point of view of component fatigue design, it is important to assess if VHCF-effects must be taken into account in general. Focusing on reliability there are two general effects which have to be considered: failure origin with contact to atmosphere or media and failure origin inside the material. These two effects must be considered separately.

2. **Fatigue Design Considering VHCF-Effects**

Fatigue designing of components is performed based on a comparison of loading and strength (Fig. 1). This procedure is done during the pre-design phase based on simulation of component stresses or strains and the prediction of material strength at the component. Taking testing of component samples into account, Woehler-Curves (S/N-curves) and Gassner-Curves are compared with measured load spectra. For both approaches an assessment of the failure probability, often calculated as a safety factor, leads to a reliability assessment.

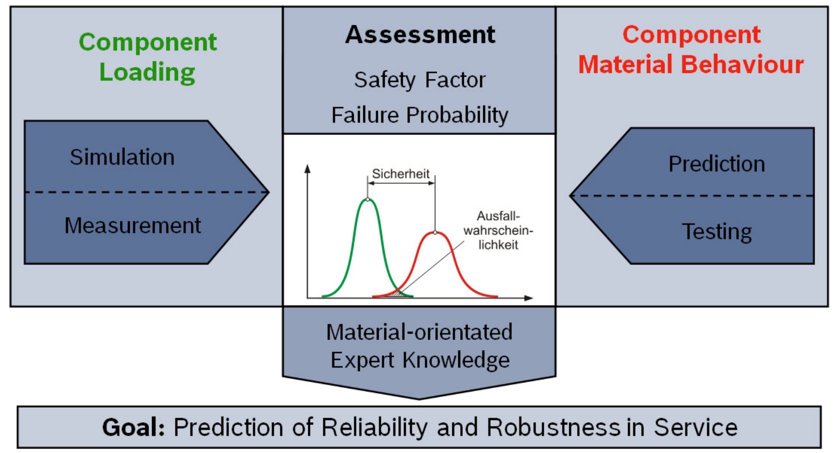

Figure 1: Fatigue designing concept

It is obvious, that additionally to the mean values of loading and strength the scattering will affect the failure probability very significantly. Focusing on cyclic loading, the S/N-curve may show unexpectedly a significant decrease above load cycles of $N > 10^7$. This effect is well known as Very High Cycle Fatigue (VHCF) and is the general topic of a sequence of up to now five international VHCF-conferences since 1998, the latest at Berlin in 2011 followed by VHCF6 at Chengdu, China in 2014.

Due to this performance of the S/N-curve the failure probability increases with rising numbers of cycles even in a region with assumed constant fatigue strength. Presuming a constant amplitude service load spectrum the probability of failure respectively the "real safeties" j_{real} can be calculated as shown schematically in Fig. 2 [1].

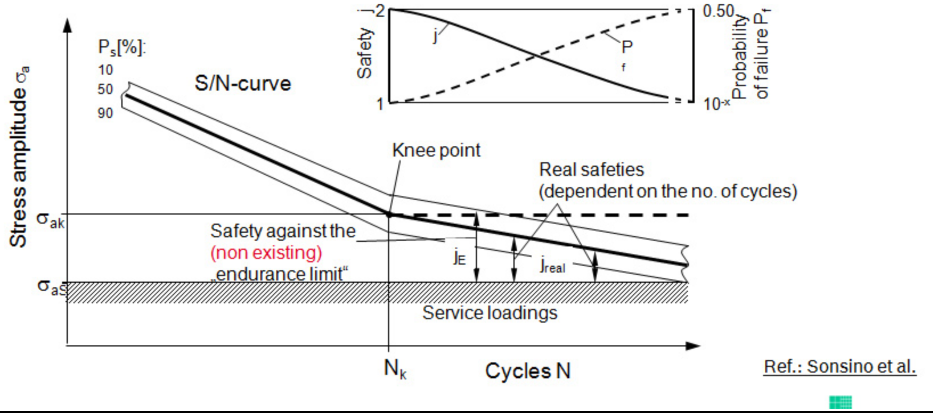

Figure 2: Safety concept for assumed constant amplitude loading taking decrease of fatigue strength at very high cycles into account [1]

In practice, load spectra show very different shapes depending on the technical system and the user profiles. In case of severe variable amplitude loadings the reliability assessment refers as well to the S/N-Curve and in addition to the Gassner-Curve, which has to be carried out as a variable amplitude test [3].

3. **Example: Fuel Direct Injection Pump**

Fuel injection systems are core elements of modern automotive engines. Actual system pressures are outlined at about 200 bars. The high-pressure part of the system consists of a fuel pump, the fuel distributer and mounted injectors to provide the combustion chambers with fuel [7].

Fig. 3 shows the principle design of a high pressure pump of a Gasoline Direct Injection (GDI) system. Occurring as cyclic loading, the fuel pressures inside the components are complex time sequences influenced by the system application, hydraulic behavior at local component sites, car mission profiles and additionally by specific driving characteristics of the operators.

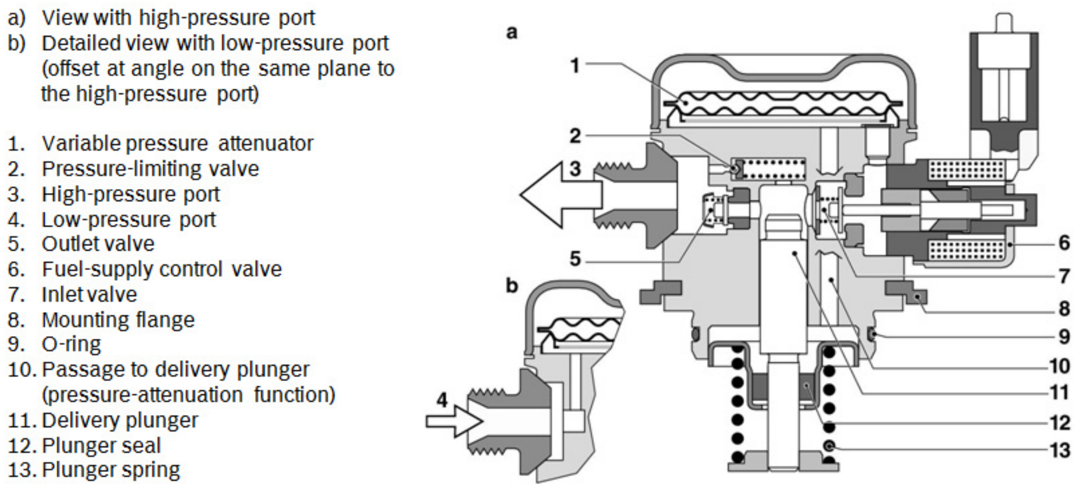

Figure 3: Single-Barrel High Pressure Pump for 2nd Generation Gasoline Direct-Injection (GDI)-Systems [4]

Usual mileages for passenger cars are hundreds of thousands of km, hence a lot of cycles have to be expected. Fig. 4 shows a typical load spectrum for a high-pressure GDI pump, where very high cycles are occurring in combination with high pressure amplitudes.

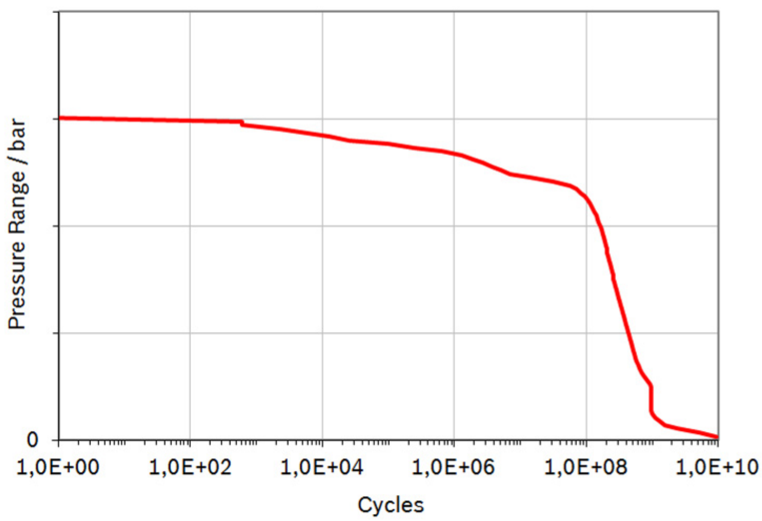

Figure 4: Example of Pressure Load Spectrum in a Fuel Direct Injection Pump

Another important issue is the composition of the fuel. In order to improve the CO_2 footprint bio-fuels are increasingly used. Bio-fuels are fuels which are produced from living organisms or from by-products. For example E10 is a typical gasoline fuel in Europe which contains a maximum proportion of 10% ethanol. Depending on the additives in the fuel corrosion fatigue effects might occur and have to be considered for the fatigue release of the components.

4. **Material Behaviour at Very High Cycle Fatigue (VHCF)**

Having identified the necessity of dealing with possible VHCF-effects due to high number of cycles in combination with the shape of the load spectra, the next question concerning fatigue failure reliability is the behaviour of the chosen materials and joints subjected to VHCF.

It should be underlined, that a combination of different testing procedures and set-ups had to be developed to have an integral answer on VHCF-risks due to material, surface and media exposition. These tests have been outlined using notched, smooth and joined specimens respectively. In this sense the special VHCF-failures inside the material and corrosion fatigue effect at the surface must be identified and transferred to the component. To use these results of specimen for an assessment of components subjected to VHCF, low differences in material and stress state between specimen and component respectively are required.

In components fatigue failure typically occurs in high-stressed regions with stress gradients. In order to obtain results with better transferability to components the research investigations are carried out with notched specimens. The notch geometry and the stress gradient were adjusted by comparing with critical local stress states at the components. The grinded notch geometry of the fatigue specimens, the mechanical properties at tensile testing and the microstructure of the used martensitic steel containing numerous primary carbides are shown in Fig. 5.

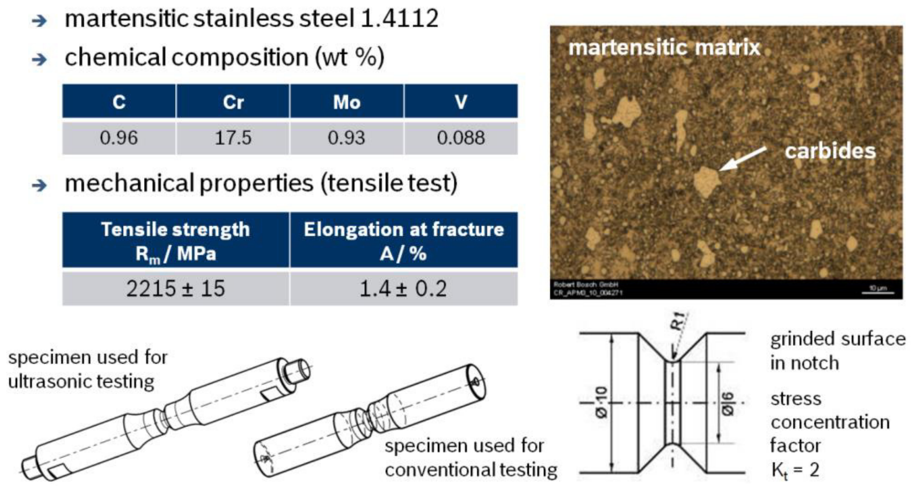

Figure 5: Material Properties and Microstructure of the Martensitic Stainless Steel 1.4112 (X90CrMoV18) and Specimen Geometry for Fatigue Testing

Fatigue tests were performed in axial loading mode using two different systems: an electromagnetic testing system operating at 150 Hz and a piezo-electric testing system type BOKU Vienna [6] operating at 20 kHz. The stress ratio of all tests was R = 0.1, which was adapted from the stress ratio at internal pressurized components. To carry out fatigue tests in fuels an explosion protected specimen chamber is required due to safety reasons. Details of the testing procedure and set-up are outlined in [2, 6].

Fig. 6 shows this complex answer considering a high strength wear resistant steel subjected to fatigue at lab atmosphere up to a very high number of cycles [2]. In this context it should be pointed out, that ultrasonic fatigue testing at specimens can provide similar lifetimes comparing to low frequency testing equipments, if failure processes are comparable. Therefore as an important precondition the testing techniques and failure mechanisms have to be studied very careful, and intrinsic frequency effects depending on material state have to be taken into account.

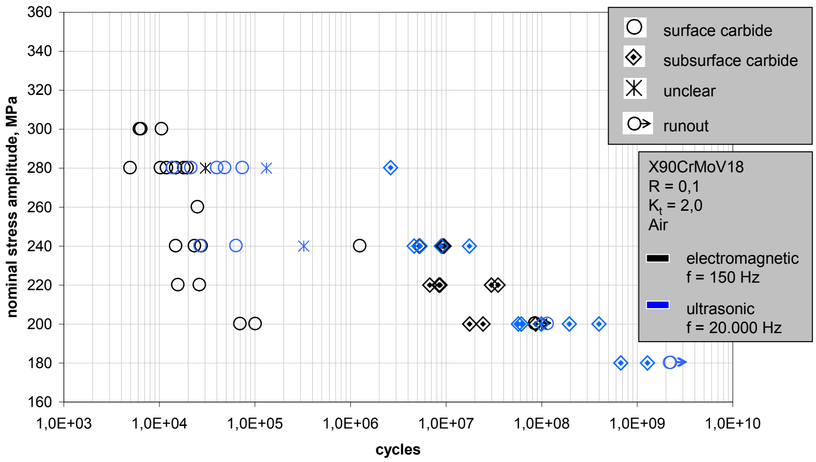

Figure 6: S/N-diagram and failure mechanisms of fatigue loaded specimens (notched K_t=2, stress ratio R=0,1) of high strength steel measured at loading frequencies of 150 Hz and 20 kHz [2]

5. **Fatigue in Biofuel**

Fig. 7 shows the S-N diagram at testing frequency 150 Hz in air and in biofuel E85. It can be observed from these results that the fatigue strength decreases remarkably in biofuel E85 (Ethanol content 85%). The decrease of fatigue strength at 10^6 cycles caused by E85 is approximately 35 %. The experimental results also showed that fatigue life at high stress levels rsp. low numbers of cycles to failure is not significantly affected by biofuel media, as the lifetime in E85 at higher nominal stress levels (σ_a= 280 MPa) was comparable to the lifetime in air. In this short term testing the damage is obviously mainly caused by mechanical cyclic loading. This is in accordance to the knowledge of corrosion fatigue effects. Additionally to this corrosion fatigue test, long-term exposure tests without mechanical load have been conducted. During the exposure time of 168 h (this duration corresponds approximately to 9 x 10^7 cycles at the testing frequency of 150 Hz) no visible corrosive attack, e. g. localized pitting corrosion on the surface of the specimen was found. Obviously a corrosion effect during cyclic loading only occurs in combination with surface fatigue effects like extrusions and intrusions.

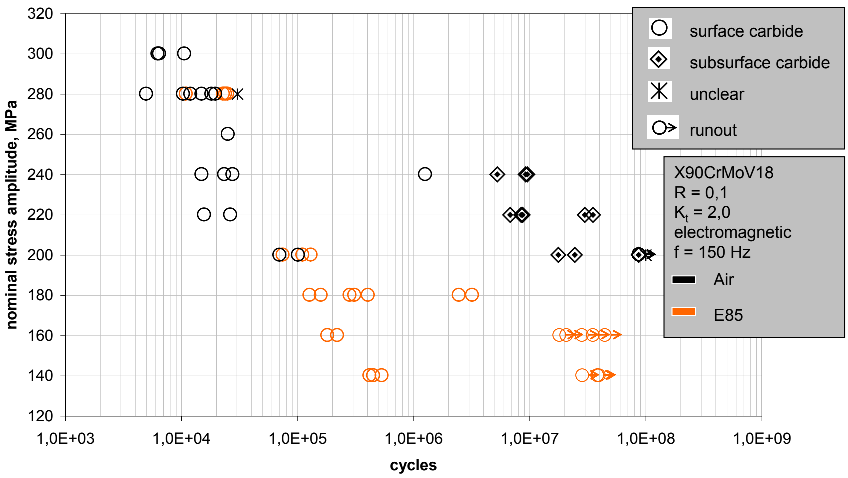

Figure 7: S-N results of X90CrMoV18 tested at 150 Hz (R = 0.1) in air and in biofuel E85

Similar to the investigation in air, the fracture surfaces of all failed specimens were observed by SEM. When tested in E85, solely surface carbide crack initiation is observed. For tests in E85 the S-N curve of surface carbide fracture seems to be low enough to mask internal carbide failure. As it can be seen in Fig. 8b/c, there is no visible corrosive attack in the area of the carbide. This is in agreement with previous investigations [8], in many cases there is no visible difference between a fatigue crack and a corrosion fatigue crack. But there are some other indications for a corrosive effect. Firstly, for tests in air in all cases fatigue failure was essentially initiated at one single carbide, but for test in E85 there are several crack origins at one specimen (Fig. 8a). Secondly, in E85 even smaller carbides initiated fatigue cracks compared to air. This shows that there is a degradation of the local fatigue resistance at stress concentrations in the surrounding of carbides due to corrosive effects of bio-fuel compared to the tests in air. Fracture mechanic approaches as carried out in [2] show the evidence of this theory.

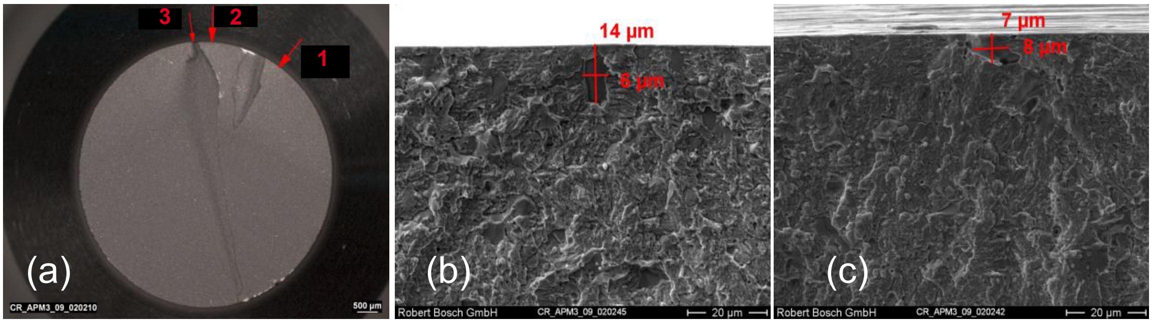

Figure 8: Crack initiation in biofuel E85 (S_a = 140 MPa, N_f = 4,5 x 10^5, f = 150 Hz):
(a) complete fracture surface with several crack initiation sites 1, 2 and 3,
(b) detail at crack initiation site "1",
(c) detail at crack initiation site "2"

6. Approach Taking VHCF Effects into Account

For component aspects the location of fatigue damage depending on the surface and subsurface sensitivity might show a complex and nonlinear influence on to the number of cycles until failure. This concurring situation leads to a final S/N curve and can be explained by partly hidden local S/N curves surface and interior failure, Fig 9. Extended measures to increase the VHCF-lifetime of components - for example by reduction of internal inclusions or material defects - may not have the expected effect, if possible surface failures – for example due to surface machining effects – are not improved in parallel. An approach to take surface defect distributions into account by using fracture mechanic approaches and probabilistic calculations is shown in [9].

In practice the estimation of the fatigue limit of the component as a function of the number of cycles in service (e.g. load spectra of passenger cars components: 10^9 to 10^{10} cycles) is still a big challenge. One reason is the lack of high-frequency testing component rigs for an economic VHCF testing. Assuming a fatigue design based on variable amplitude loading, this leads to an unavailability of validated designing concepts (resp. damage sums) for the damage accumulation in the VHCF regime.

One solution is to carry out long-time fatigue tests in system environment (e.g. in fuels) using demonstrators, e.g. notched specimens, and to develop and verify designing and testing concepts to transfer the results from specimens to the component. Examples using notched specimens made of an aluminum and steel alloy are shown in [5]. One of the results was that in the examined cases the application of the measured Miner sum using HCF results used for a damage accumulation in the VHCF regime lead to conservative lifetime results.

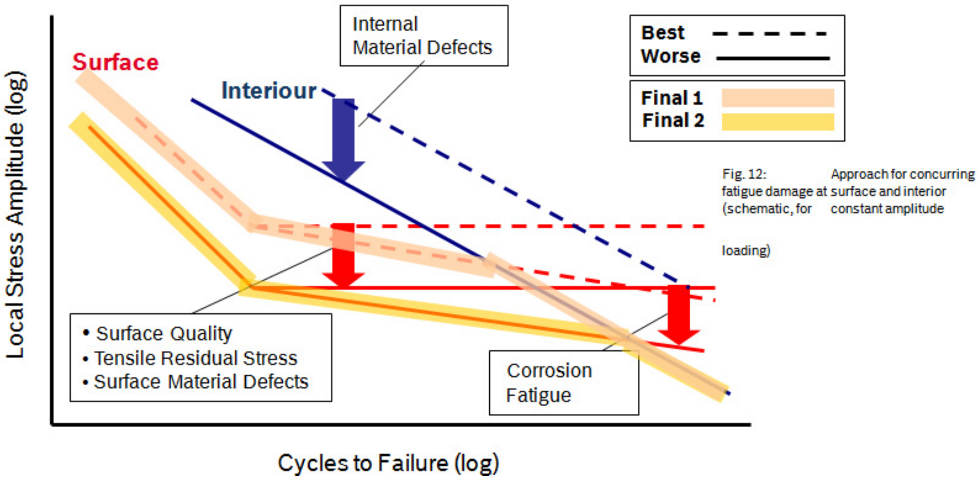

Figure 9: Schematic view on S/N-curves for different failure modes and derivation of final S/N-curves at components [3]

7. Conclusions and Outlook

The assessment of component fatigue reliability at very high cycles requires very long testing times and may result in low statistical significance, if test frequencies cannot be increased properly. In these cases, for example at internal pressure loaded components, the specimen testing fill up the missing information in the VHCF-area concerning failure modes and reduction of lifetime at components. Adequate advanced testing procedures are necessary to simulate important component influences, as material condition, load spectra, stress state and environment media for example. Nevertheless it must be suggested to verify these approaches by some extended tests on components. In this context new testing equipments based on resonant systems are required.

As contribution to a successful use of new materials and new manufacturing states the failure risks at VHCF can be assessed in early stages of the development process.

References

[1] Sonsino, C. M.: Course of SN-curves especially in the high-cycle fatigue regime with regard to component design and safety. Int. J. of Fatigue 29, 2007

[2] Schmid, S. et al.: Effect of frequency and environment on very high cycle fatigue behaviour of a high strength steel. Proceedings of the 5th Int. Conference on very high cycle fatigue (VHCF5), Berlin, 2011

[3] Bacher-Hoechst, M. et al.: Current developments and trends on structural durability. Proceedings of the 2nd Symposium on Structural Durability in Darmstadt (SoSDiD), 2008

[4] Robert Bosch GmbH: Automotive handbook, SAE International, 2011

[5] Issler, S. et al.: Fatigue design for components under variable amplitude loading in the very high cycle fatigue area. Proceedings of the 2nd DVM / ASTM International Conference on variable amplitude loading (VAL2), Darmstadt, 2009

[6] Mayer, H.: Fatigue crack growth and threshold measurements at very high frequencies. International Materials Reviews 44 (1999) 1, 1-34

[7] Bacher-Hoechst, M. et al.: How to deal with Very High Cycle Fatigue (VHCF) effects in practical applications. Materials Testing 54 (2012) 11-12

[8] Speckardt, H. ; Gugau, M.: Korrosion und Korrosionsschutz von Metallen. In: Dubbel - Taschenbuch für den Maschinenbau, 2001

[9] Fayard, A. et al.: Development and application of a probabilistic fatigue prediction model for size distributed surface defects. Proceedings of the 18th European Conference on Fracture (ECF18), 2010, Dresden, Germany